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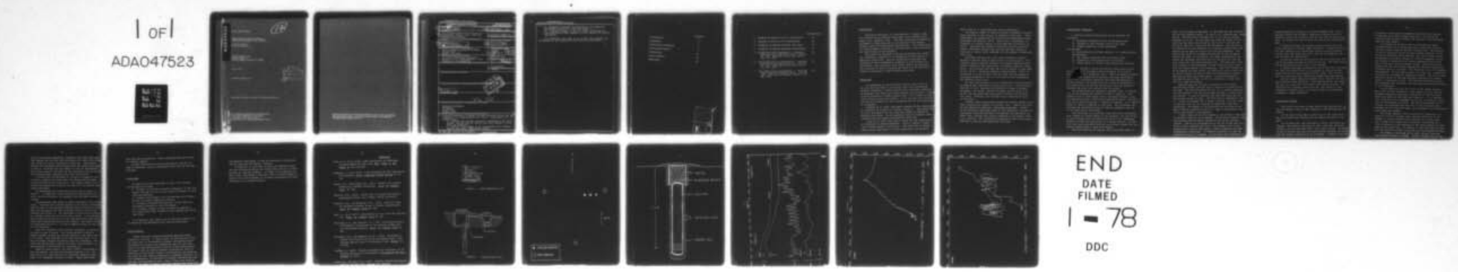

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PRELIMINARY RESULTS FROM A SHALLOW BOREHOLD TILT ARRAY

James Lewkowicz
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A shallow borehole tilt array has been installed within the boundaries of a deep borehole tilt array. Preliminary conclusions are:

(1) Rainfall has obvious transient influences on the tilt signal, and may also be causing long term changes in drift rate and direction.

(2) Diurnal tilts appear to be contaminated with thermal-elastic and direct temperature effects.

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(3) Barometric pressure fluctuations do not cause any noticeable variation in the tilt signal. and

(4) A cursory attempt to pack the sand, by banging on the installation pipe, appears to have reduced the instrument drift.

It is possible that some or all of the above effects can be removed by the appropriate data analysis techniques.

Contents

Illustrations

Introduction

Internally consistent (1% amplitude and 3° phase), tidal tilt signals can be obtained using deep (20 m) borehole tiltmeters (e.g. Cabaniss, 1974). The major advantage of operating tiltmeters in deep boreholes is the isolation from surface effects (such as meteorological disturbances). The disadvantage of a deep borehole tiltmeter is the high cost of the instrument and the drilling of the borehole.

This study was designed to develop techniques for installing tiltmeters in shallow (~3 m) boreholes for the purpose of monitoring tidal tilt. Such an installation would have the advantage of being inexpensive, compared to deep borehole installations, thus allowing a much larger area to be monitored. The logistics of such an installation would also be relatively simple in comparison to deep borehole operations.

Background

An examination of the literature reveals that little if any work has been done in extracting tidal tilt from shallow borehole tiltmeters. Various workers have installed tiltmeters in boreholes, but these are usually greater than 5 meters in depth. Drilling boreholes at depths greater than 5 to 20 meters in many cases involves going into bedrock. It is the high cost of drilling and the logistics of such a procedure that we are attempting to circumvent.

Beaumont et al (1970) described a method for the installation of tiltmeters at a depth of 5 meters (Figure 1). The sensitivity of their instruments was less than that needed to adequately measure earth tides. We are therefore unable to evaluate their technique for the purpose of monitoring tidal tilt.

Allen et al (1973) have used a method for the installation of tiltmeters in shallow boreholes. Figure 2 shows a cutaway view of their typical installation. They were able to record, under certain conditions, at tidal sensitivity, and measured

drift rates of .4 microradian per month (urad/month).

The largest number of shallow borehole tiltmeters currently being operated in this country is located in California. These instruments are operated by the United States Geological Survey (Mortensen and Johnston, 1975). The U.S.G.S. instruments are installed in a manner similar to that described by Allen et al (1973). Mortensen and Johnston filter the raw tilt signal to remove frequencies greater than one cyle per day, making it difficult to assess their technique for the purpose of measuring tidal tilt.

Morrissey and Harrison (1977) have installed a shallow borehole tiltmeter array on Adak Island in the Aleutians. Preliminary results indicate coherent tilt signals between instruments 10 meters to 400 meters apart, and drift rates of 1 urad/month. The technique that they use is also similar to that used by the U.S.G.S. Morrissey (personal communication, 1976) is interested in using the data from the array for the purpose of earthquake prediction, and it is not clear if the instruments are measuring tidal tilts.

We feel that Beaumont et al's installation is more difficult to prepare than those being used by the U.S.G.S. We have evaluated the U.S.G.S. technique and modified it where we thought necessary. The method used by Morrissey was not known to us at the time the plans were being made to install our shallow tilt array. Reference will be made to his installation later in the report.

Various other workers have reported on shallow borehole tiltmeter installations (Beaven and Bilham, 1977; Hade et al, 1977) for the purpose of observing earthquake precursors. Neither of the techniques described seems to have adequately isolated the instruments from meteorological disturbances for separation of tidal tilts, judging from results presented at the Spring (1977) A.G.U. meeting. The installations apparently have to be further modified to provide more mechanical stability.

Installation Technique

A shallow borehole installation should maximize the following:

1) Mechanical stability of the installation site.
2) Coupling of the tiltmeter case to the crust.
3) Thermal stability of the instrument.

and minimize:

1) Site response to surface effects, i.e. meteorological disturbances.
2) The anomaly caused by the installation site.
3) Complexity in the preparation of the site.
4) Effort needed to retrieve and emplace the tiltmeter.

It was decided to place the shallow installation within the boundaries of the deep (∿100 m) borehole tilt array at Maynard (Cabaniss & McConnell, 1977). This, as shown in Figure 3, would allow comparison of the data with deep instruments. As the deep instruments should be free from the majority of surface effects, this would allow us to make some estimate of the stability of the shallow installation site and possibly separate the local site effects from the signal.

Site preparation was started in November 1976. A cutaway view of the installation method is shown in Figure 4. The procedure was to first auger a hole, nominally vertical, into the overburden using a motor-driven post-hole digger. The borehole was ∿4 meters deep and ∿.3 meters in diamter. It is approximately 20 meters to bedrock in this area. The topography surrounding the installation site is radially symmetric and flat for at least 350 to 400 meters.

The overburden is an alluvial sand with minor interbedded clay visible at various depths in the borehole. We did not dig a large diameter hole, as required by the U.S.G.S. technique, because we house the electronics in a nearby trailer. We also think the large excavated hole and road culvert placed near the surface could create a large site anomaly.

Once the borehole was augered, with care being taken to

drill it as straight as possible, it was ready for the installation of the borehole casing. We used P.V.C. plumbing pipe, schedule 80. The wall has a thickness of 1.27 cm, and an outside diameter of 8.9 cm. We felt that this would be easier to work with than the steel casing used by the U.S.G.S., and the stability of the P.V.C. pipe would be comparable. The pipe had a cap cemented onto the downhole end to prevent ground water from seeping up the pipe and varying the sand pore pressure. The pipe itself serves to increase the baseline of the tiltmeter. Without the pipe, it is possible that small perturbations may affect the tiltmeter case that are not indicative of even the very local tilt, let alone regional tilt. The pipe also allows ready access to the instrument, without having to dig a large hole for either removal or installation. When the tiltmeter is to be removed for some reason, an industrial vacuum cleaner can be used to remove the sand in which the instrument is packed. More will be said about this later. A further advantage to the plastic pipe is that it will not corrode as a steel pipe will in a damp environment.

Once the pipe was in place, a mixture of 50% 20-mesh and 100-mesh foundry sand was used to backfill the void around the pipe. The sand was primarily SiO_2, but a certain amount of clay was present. The top of the pipe was kept $\sim$.5 meter below the surface. A piece of chimney flue pipe made from clay was then placed around the pipe. The flue pipe is rectangular and is .3 meter in diameter and .6 meter in length. Care was taken so that the flue was not touching the pipe and it was then backfilled. The purpose of the flue pipe was to allow a minimum of surface coupling of the P.V.C. pipe to the surface, but still allow access to the borehole.

A small amount of sand was placed at the bottom of the pipe to provide a base for the tiltmeter. The biaxial tiltmeters used were manufactured by Radian Corporation and can be remotely leveled. There is an alignment pin on the top of the case into which a metal alignment rod fits. The alignment rod is then aligned with a mark at the surface, whose orientation has been independently determined. It should be possible to align the tiltmeters axes to $\pm$.5 degree. At this point the instrument is

leveled manually by moving it with the alignment rod. Once it has been leveled and aligned a temperature sensing device is placed on top of the tiltmeter case and the pipe is filled with sand. No attempt was made to pack the sand in the installation pipe.

A second tiltmeter was placed in the same hole with the first instrument to measure their coherency. A third tiltmeter was then installed in a second hole using the same procedure. A third hole (the three holes were colinear and numbered from East to West) was left vacant.

An end cap identical to the bottom cap was fitted over the top of the casing to keep the sand inside dry. The power/signal cables were fed through a slot in this endcap.

A second flue pipe was placed on top of the first flue pipe. The joint was sealed with R.T.V. compound to prevent surface water from running down along the P.V.C. pipe. The inside of the flue pipes were then filled with bagged styrofoam pellets.

The raw signal cable was brought into a low-pass (200 sec.) filter before being amplified. After amplification, the signal was sent to a digitizer and sampled every thirty seconds. The digitizer has a dynamic range of 86 dB. The signal is then recorded on magnetic tape. The analog signal is concurrently displayed on chart recorders.

Preliminary Results

The initial few weeks of data showed that parallel axes on the instruments in Hole 1 were coherent at the semi-diurnal frequency.

It was later found that a ground loop in the electronics may have caused this coherency and at present the data is suspect.

At the same time, the instrument in Hole 2 failed and was removed. The shallow instrument in Hole 1 was then installed in Hole 2, but covered with only a thin layer of sand. We wanted to see if filling the pipe with sand actually improved the mechanical and thermal stability of the tiltmeter. Instead of the sand,

we placed a short roll of household insulation into the top of the hole to provide thermal stability. If filling the pipe with sand could be avoided, the removal of the instrument would be much simpler.

An analysis of the data from the instrument in Hole 1 indicated there was a semidiurnal wave on the axis oriented E-W and a diurnal wave on the axis oriented N-S. The majority of tilt at this site is due to ocean loading (Cabaniss, 1974) in the E-W direction which indicates that the N-S tilt may be thermoelastic in origin (Figure 5). The N-S component of tilt was roughly in phase with the outside temperature and tilted down to the North when the ground warmed. The diurnal tilts disappeared when the outside temperature (and hole temperature) variations were at a minimum. The amplitude of the E-W component, approximately .30 urad peak-to-peak, also died off; suggesting an additional instrumental temperature effect. The E-W M_2 tidal amplitude, based on the deep borehole instruments is approximately .2 urad peak to peak. The amplitude reductions in the E-W component were consistent with the temperature specifications of the instrument.

A main feature of the tilt trace is the sudden change in drift rate of both components. This change in drift rate was probably caused by a mechanical releveling of the instrument which took place at this time (see Figure 5). It is possible that the drift rate is dependent on the way in which the instrument is mechanically releveled. The drift rate before the instrument was releveled was less than 1.0 microradians/month, measured over an 8-day time span, and increased to 16 microradians/month after the relevel.

The abrupt change in drift direction was apparently related to a 8.75 cm rainfall that occurred just prior to the change. A drop in pressure also occurred at the same time, but a larger, more rapid drop in pressure, accompanied by a 2.54 cm rainfall at the beginning of the record showed no influence on the ground tilt. It appears in this case that the rainfall had more of an effect on ground tilt than pressure changes.

An attempt to calculate the M_2 tidal ellipse using the least squares method of Vaníček (1970), solving only for M_2,

N_2 and the outside temperature, yielded a semi-major amplitude that agreed with the deep hole instruments to within 20%, phase lag within 5%, and an orientation within 20%. Much poorer results were obtained using the data from the second instrument in Hole 2. We think that the absence of sand in the borehole was a major cause of the drift of the instrument, as the instrument has previously displayed much lower drift rates.

A vector plot of Instrument #1 is shown in Figure 6, and it shows a general S-W trend whose initiation was coincident with the relevel of the instrument. The sudden change in direction was apparently caused by the same 8.75 cm rainfall mentioned previously.

An enlargement of the previous vector plot is shown in Figure 7. It shows the major direction of semi-diurnal tilt was in the E-W direction, in agreement with the deep borehole results.

Two approaches were taken to reduce the drift of the instruments. The first was a remote relevel of one of the instruments. This was made in the direction opposite that in which the instrument was releveled at the time an abrupt change in drift rate occurred (see Figure 5). The instrument is releveled by means of a movable plate that is driven with a screw. It is possible that turning the screw so as to lift that plate may cause less drift than allowing the plate to be lowered. The remote relevel was performed only on #1; it had no apparent effect on the drift of the instrument.

When the tiltmeters were initially installed, no attempt was made to pack the sand. The second approach involved a nominal attempt to pack the sand by banging on the top of the P.V.C. pipe. This resulted in the sand settling about 1 cm. The instrument required releveling after this procedure. The drift was substantially reduced from about 100 urad/month to approximately 15 urad/month, for instrument #2.

Based on these results, the sand in Hole 1 was packed by the same method. The sand settled approximately 7 cm. The drift rate on #1 declined from 16 urad/month, based on eight days, to 1 urad/month, based on 14 days. These drift rates

were for axes oriented E-W. Drift variations may also be due to rainfall effects.

Further modifications of the installation site will be made as necessary, after a sufficiently long data set has been analyzed.

Conclusions

In light of the work performed to date, the following conclusions can be made:

1) Rainfall has obvious transient influences on the tilt signal, and may also be causing long term changes in drift rate and direction.

2) Diurnal tilts appear to be contaminated with thermal-elastic and direct temperature effects.

3) Barometric pressure fluctuations do not cause any noticeable variation in the tilt signal.

4) A cursory attempt to pack the sand, by banging on the installation pipe, appears to have reduced the instrument drift.

It is possible that some or all of the above effects can be removed by the appropriate data analysis techniques.

Future Efforts

Future work will involve performing additional tidal analyses on the data. A recent paper by Wood and King (1977) has shown that it is possible to predict and possibly remove the effects of rainfall and temperature from the tilt data. There is an Army meteorological station located approximately 200 meters from the shallow borehole installation, which is providing us with hourly values of precipitation and radiation. We record on site surface temperature, barometric pressure, and hole temperatures. We have been in contact with Wood and King, and they have provided us with a copy of their data analysis program. In order to obtain consistent results that agree with

the deephole instruments, it may be necessary to pre-process the raw data from the shallow borehole.

In addition, we have been in touch with Sean Morrissey. The main difference between our installation and his, is that he does not case his borehole. In light of his reported low drift rates, (Morrissey & Harrison, 1977), we have decided to install the third tiltmeter (it is being repaired by the manufacturer) in an uncased borehole.

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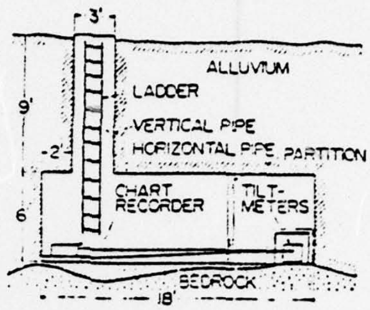
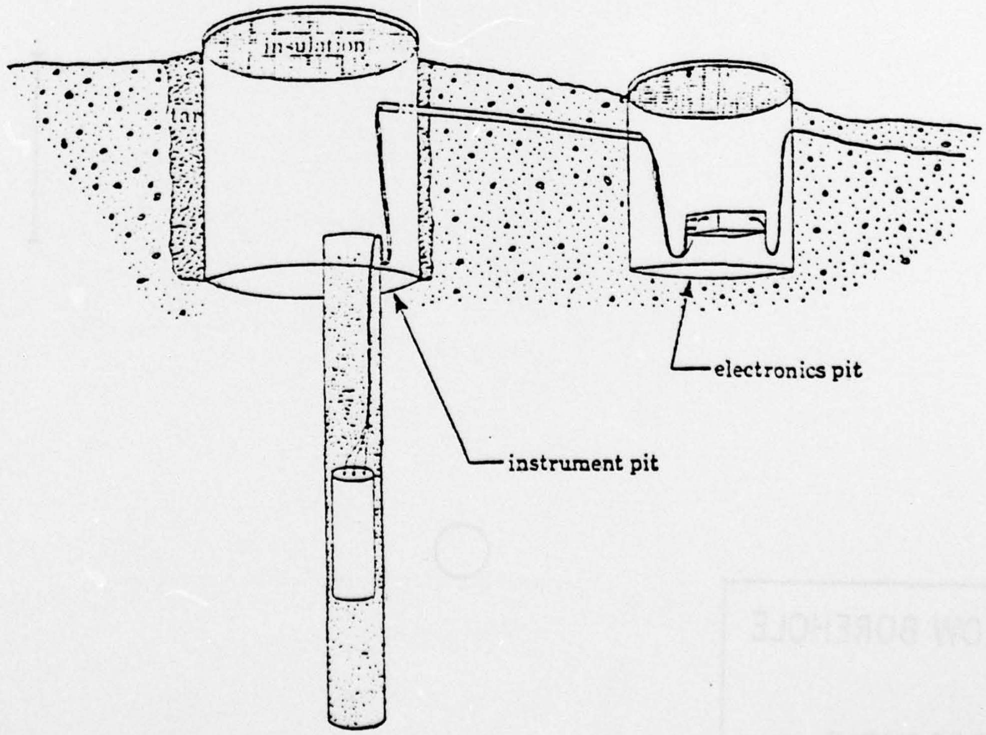


Figure 1. (after Beaumont et al)



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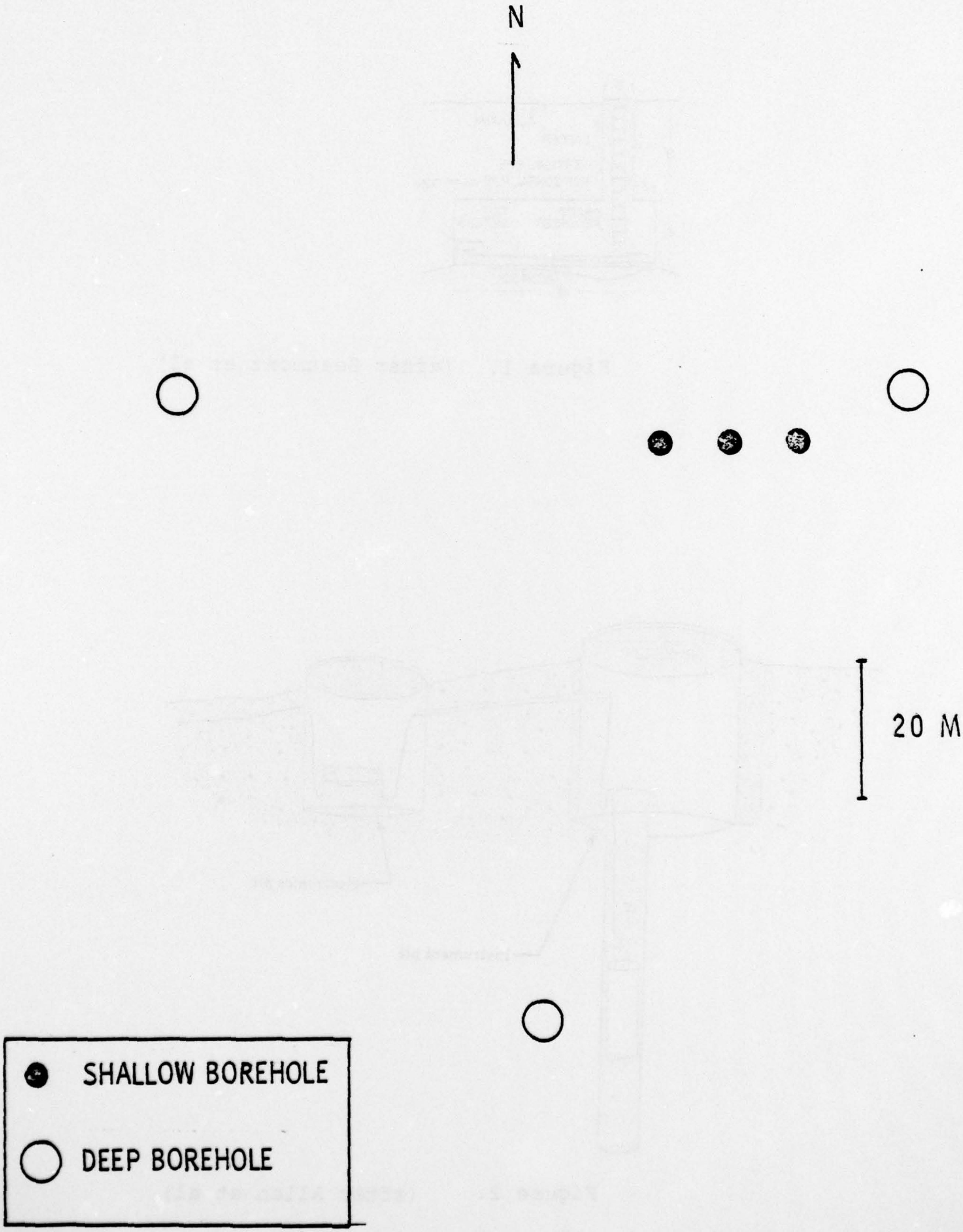

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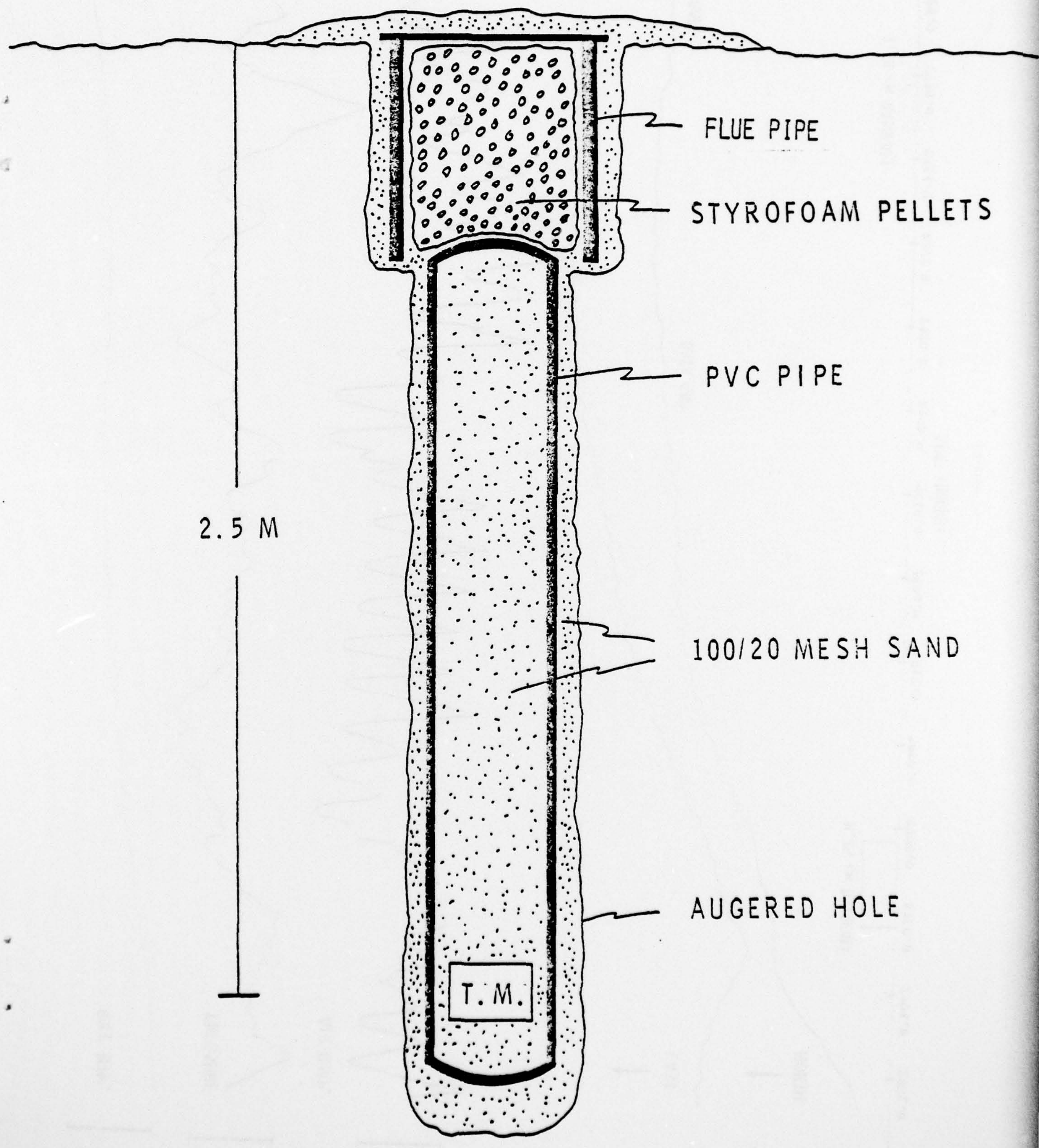
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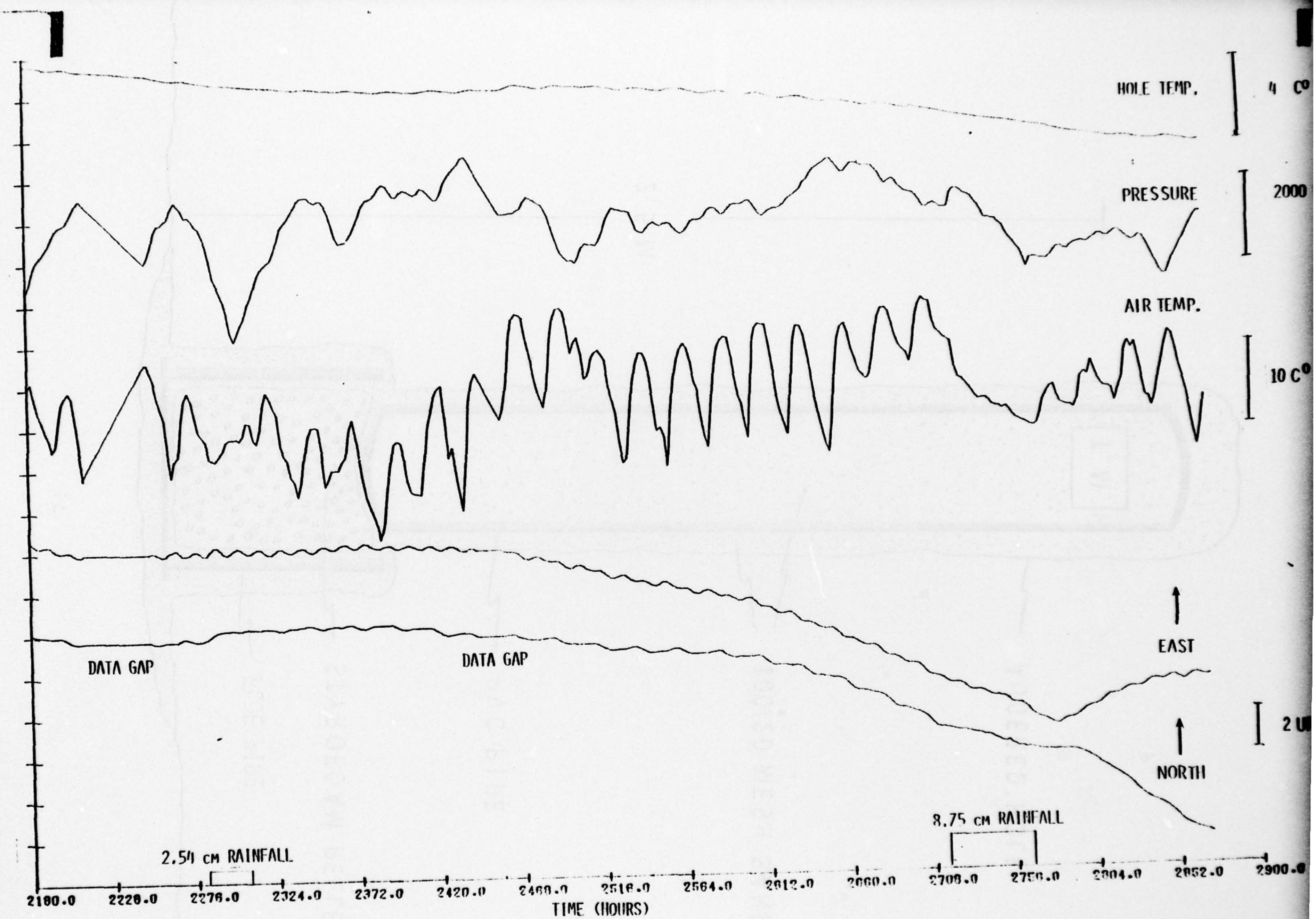
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Figure 5.

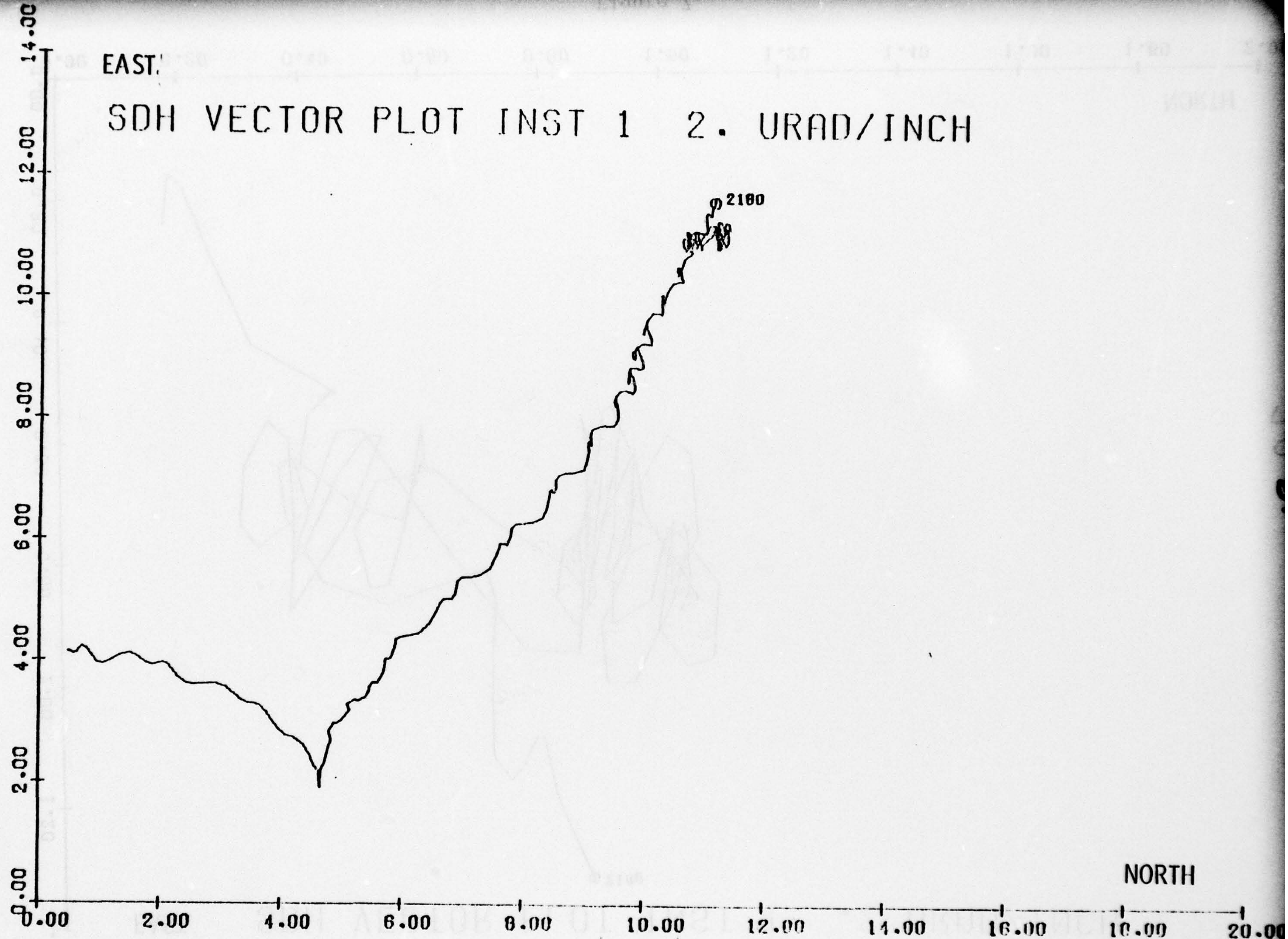
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Figure 6.

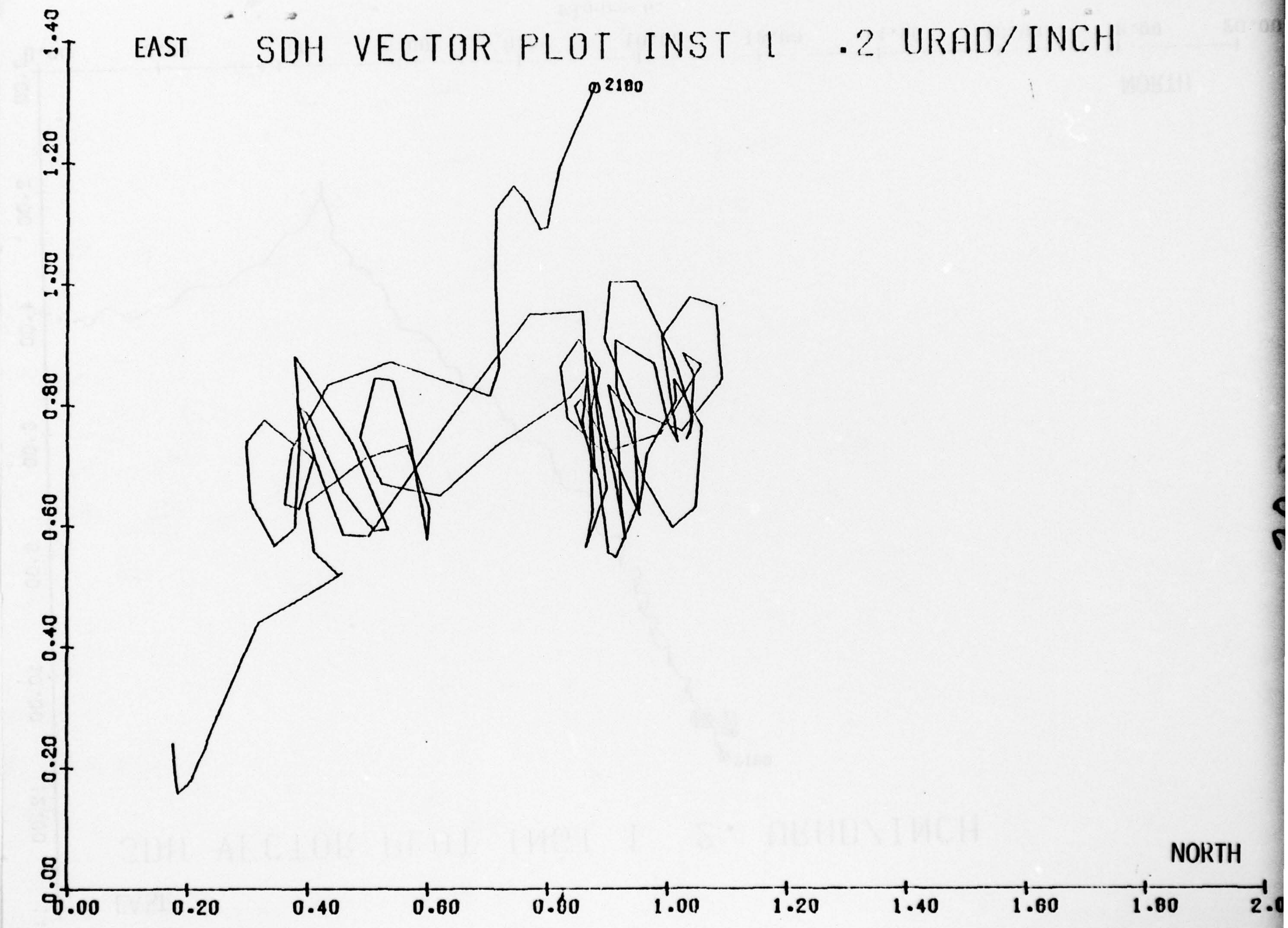
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Figure 7.